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GaAs Photonic Integrated Circuit (PIC) Development for High Performance Communications

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Abstract

Sandia has established a foundational technology in photonic integrated circuits (PICs) based on the (Al,Ga,In)As material system for optical communication, radar control and testing, and network switching applications at the important 1.3μm/1.55μm wavelengths. We investigated the optical, electrooptical, and microwave performance characteristics of the fundamental building-block PIC elements designed to be as simple and process-tolerant as possible, with particular emphasis placed on reducing optical insertion loss. Relatively conventional device array and circuit designs were built using these PIC elements to establish a baseline performance standard; to assess the impact of epitaxial growth accuracy and uniformity, and of fabrication uniformity and yield; to validate our theoretical and numerical models; and to resolve the optical and microwave packaging issues associated with building fully packaged prototypes. Novel and more complex PIC designs and fabrication processes, viewed as higher payoff but higher risk, were explored in a parallel effort with the intention of meshing those advances into our baseline higher-yield capability as they mature. The application focus targeted the design and fabrication of packaged solitary modulators meeting the requirements of future wideband and high-speed analog and digital data links. Successfully prototyped devices are expected to feed into more complex PICs solving specific problems in high-performance communications, such as optical beamforming networks for phased array antennas.

Acknowledgment

Many individuals are responsible for the success of this program. The principal investigators are M. G. Armendariz, G. R. Hadley, M. J. Hafich, B. E. Hammons, V. M. Hietala, H. Q. Hou, J. F. Klem, S. H. Kravitz, J. Reno, R. J. Shul, R. E. Smith, C. T. Sullivan, G. A. Vawter, and J. R. Wendt.

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Contents

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Objective

The objective of this program has been to establish a foundational technology in photonic integrated circuits (PICs) based on the (Al,Ga,In)As material system for optical communication, radar and antenna control and testing, and network switching applications at the important 1.3μm/1.55μm wavelengths. As these operating wavelengths are substantially below the bandedge, and the primary modulation mechanism is the linear electrooptic effect, we anticipate that these materials are quite hard to damaging radiation effects and can be engineered in device geometries capable of operating from DC to deep into the millimeter-wave range. These attributes may therefor become very attractive to the nuclear weapons community (primarily for its spaceborne surveillance and treaty verification missions), the military and commercial space applications community, and the terrestrial fiber data and telecommunications communities. While beyond the scope of the present program, the potential exists to integrate PICs monolithically with electronic circuits made from epitaxially compatible materials. Indeed, many of the requisite fabrication steps developed for PICs under this program were borrowed from the knowledge base at Sandia and elsewhere in GaAs digital integrated circuits and GaAs millimeter-wave and microwave integrated circuits (MMICs) to maintain the capability for eventual integration.

We investigated the optical, electrooptical, and microwave performance characteristics of the fundamental building-block PIC elements designed to be as simple and process-tolerant as possible, with particular emphasis placed on reducing optical insertion loss. This has been a key issue for the semiconductor PIC community since the fiber-PIC-fiber insertion loss had been prohibitively large, with typical values in excess of 20 dBo (40 dBe). This loss problem has been substantially solved as a result of progress under this program. Relatively conventional device array and circuit designs were built using these low-loss PIC elements to establish a baseline performance standard (versus state-of-the-art lithium niobate and chromophore-doped polymer devices); to assess the impact of epitaxial growth accuracy and uniformity, and of fabrication uniformity and yield; to validate our newly-developed theoretical and numerical models for photonic devices and circuits; and to resolve the optical and microwave packaging issues associated with building fully packaged prototypes suitable for some system applications. Novel and much more complex PIC designs and fabrication processes, viewed as higher payoff but higher risk, were explored in a parallel effort with the intention of meshing those advances into our baseline higher-yield capability as they mature.

The application focus targeted the design and fabrication of packaged solitary modulators meeting the requirements of future wideband and high-speed analog and digital data links. Successfully prototyped devices are expected to feed into more complex PICs solving specific problems in high-performance communications, such as optical beamforming networks for phased array antennas.

Technical Accomplishments

On our baseline effort, we demonstrated record low-loss optical waveguide routing and distribution components for (Al,Ga)As PICs, including: (1) singlemode attenuations < 0.5 dB/cm (our best 0.4 ± 0.1 dB/cm), (2) right-angle turning mirror insertion loss of 0.4 ± 0.1 dB, a world-best record, and (3) excess loss of 0.4 ± 0.2 dB for lateral mode interference (LMI) 1X2, 1X4, 1X8, and 1X32 splitters, all with typically ~95% on-chip yields. These accomplishments represent a tremendous advance in the state-of-the-art of semiconductor-based PICs. The optical loss performance now surpasses nonlinearoptic polymeric devices and nearly matches that of lithium niobate devices, but of course without the many disadvantages of those material systems.

We developed an approach to velocity match (<10% mismatch) low-loss transmission line electrodes to undoped (Al,Ga)As optical waveguide modulators with ~95% on-chip yields, fabricated wideband electrooptic waveguide modulators, and developed fiber packaging for loss-limited small-signal bandwidth >50 GHz and fiber-waveguide-fiber insertion loss of <6 dB. We have theorized and then demonstrated experimentally that the use of highly form-birefringent waveguide designs are a practical solution to obtaining high-extinction ratio Mach-Zehnder interferometers, thus resolving the long-standing problem of device depolarization in semiconductor PICs. Our novel approach is based on high-index-contrast digital alloys. The origin of the otherwise unpredictable lightwave depolarization is associated with uncontrolled strain introduced by residual electrode stresses and submicron misalignment on our deeply-etched waveguide features, feature micro-roughness (esp. sidewall roughness), and crystallographic misorientation of the starting substrates. Typical interferometer extinction ratios are now routinely measured to be in the 30 dB to 40 dB range, with a best value of about 43 dB, for devices that exhibit on-chip optical losses of 2~5 dB, and half-wave voltages of 4~10 V, depending on the design specifics. This accomplishment represents a vast improvement over the previous state-of-the-art. (For example, previous Sandia art had uncontrolled extinction ratios in the 3 dB to 15 dB range with fiber-PIC-fiber losses much greater than 20 dB.)

A novel fiber-waveguide coupler has been invented and demonstrated to have ~1.5dB insertion loss with substantial misalignment tolerance, a dramatic improvement over the 8~10dB range typically expected for very high electrooptic figure-of-merit (FOM) modulators. In fact, this invention has now made high-FOM modulators relevant to a variety of defense and commercial applications. High-FOM modulators with 15.5dB (V^1 = 2.6V) and 14dB extinction ratios have been demonstrated using novel XY combiner and cutoff mesa waveguide designs, respectively, and have on-chip losses of about 7 dB.

Novel traveling-wave optical photodetectors using high-InAs-mode-fraction absorbing layers on standard low-loss AlGaAs waveguides have been invented and are being developed for wideband, high-optical-saturation-power RF applications. A novel 1X32 switch based on LMI splitters, phased-modulated arrayed waveguides and electrooptic in-plane focusing effects has been invented to address optical control problems in phased array radars.

Publications

The following thirty publications resulted from the subject program. Some of the more important publications are reprinted in the Appendices.

Vawter, G. A., C. T. Sullivan, J. R. Wendt, R. E. Smith, H. Q. Hou, and J. F. Klem, "Tapered rib adiabatic following fiber couplers in etched GaAs materials for monolithic spot-size transformation," (Invited) *to be published in IEEE J. of Selected Topics in Quantum Electron.*, (1997).

Childs, T. E., V. Sokolov, and C. T. Sullivan, "Lattice-engineered MBE growth of high-indium mole fraction InGaAs for low cost MMICs and 1.3-1.55μm OEICs," *Design and Manufacturing of WDM Devices, Proceedings of the Society of Photo-Optical Instrumentation Engineers,* Vol. 3234 (Paper 20), Dallas, TX (1997).

Sullivan, C. T., G. McClellan, T. Plut, C. Fuller, T. Bauer, M. Armendariz, V. Hietala, J. Reno, A. Vawter, D. Reiger, J. Wendt, D. Chu, R. Smith, B. Snipes, and P. Seigal, "Packaging of (Al,Ga)As photonic integrated circuits," (Invited) *1997 IEEE MTT-S Inter. Microwave Symp., Microwave and Millimeter-Wave Optoelectronic Integrated Circuit Modules: Manufacturing and Applic. Workshop*, Denver, CO (1997).

Seigal, P. K., M. G. Armendariz, D. J. Rieger, K. L. Lear, and C. T. Sullivan, "Metallization and packaging of compound semiconductor devices at Sandia National Laboratories," (Invited) *Proceedings of the 190th Electrochemical Society Meeting: State-of-the-Art Program on Compound Semiconductors XXV,* Vol. 96-15, San Antonio, TX, 158 (1996).

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McClellan, G. B., R. J. Shul, and C. T. Sullivan, "Dry etching of GaAs using an inductively coupled plasma," *32nd Annual Symposium of the New Mexico Chapter of The American Vacuum Society*, Albuquerque, NM (1996).

Sullivan, C. T., "Guided-wave optics developments at Sandia National Laboratories," *Workshop on Electro-Optics for the Next Century*, University of California at San Diego, La Jolla, CA (1996).

Vawter, G. A., R. E. Smith, B. Fuchs, J. R. Wendt, M. Hafich, and G. R. Hadley, "A rib optical waveguide with cutoff mesa isolation," *IEEE J. Lightwave Technol.*, Vol. 14, No. 2, 169 (1996).

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Shul, R. J., C. T. Sullivan, B. Snipes, G. McClellan, M. Hafich, and C. T. Fuller, "Attenuation losses in electron cyclotron resonance plasma etched AlGaAs waveguides," *Solid-State Electronics*, Vol. 38, No. 12, 2047 (1995).

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Vawter, G. A., J. F. Klem, and R. E. Leibenguth, "Improved epitaxial layer design for real-time monitoring of dry-etching in III-V compound heterostructures with depth accuracy of +/- 8 nm," *J. of Vac. Sci and Technol. A (Vacuum, Surfaces, and Films)*, Vol. 12, 1973 (1994).

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Kravitz, S. H., V. M. Hietala, G. A. Vawter, M. E. Warren, G. R. Hadley, M. G. Armendariz, J. C. Word, M. B. Snipes, J. R. Wendt, R. F. Carson, R. F. Corless, B. E. Hammons, J. F. Klem, and R. E. Leibenguth, "High performance GaAs/AlGaAs optical modulators: their performance and packaging for microwave photonic integrated circuits," *1994 Asia-Pacific Microwave Conf.*, Tokyo, Japan (1994).

Vawter, G. A., V. M. Hietala, S. H. Kravitz, and M. G. Armendariz, "Unlimited-bandwidth distributed optical phase modulators and detectors: design and fabrication issues," *Proc. of IEEE MTT-S & LEOS Top. Meeting on Optical Microwave Interactions,* Ile-de-France, France (1994).

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Patent Disclosures

The following patent disclosures resulted from the subject program:

Vawter, G. A., and R. E. Smith, "A semiconductor diode laser using a tapered rib waveguide for expanded output optical mode size," SD-5901, S-86, 546 (1996).

Smith, R. E., and G. A. Vawter, "Tapered rib adiabatic fiber coupler," SD-5588, S-82-946 (1995).

Vawter, G. A., R. E. Smith, "Cutoff mesa isolated rib optical waveguide for III-V heterostructure photonic integrated circuits," SD-5491, S-81-584 (1994).

Patents

U. S. Patent No. 5,627,929, "Integrated optical XY coupler," G. A. Vawter and G. R. Hadley (May 6, 1997)

Conclusion

This program has developed the essentials of a foundational guided-wave technology in the (Al,Ga)As material system. All the requisite building-block components have been demonstrated, most with the world's best performance in these materials. While additional developmental work is required to assure high uniformity and yield, and run-to-run repeatability of any particular device or device array, all the basic constituent components are in place. Thus, the objectives of the program have been substantially met.

Sandia is now pursuing several business opportunities focused on application-specific development of this basic foundational technology. These include the development of high-sensitivity packaged solitary 20 GHz-bandwidth microwave modulators for a military satellite applications, 1x32 optical switch matrices supporting novel optical beamforming networks for phased array antennas, and monolithic electrooptic steering systems for laser satellite communication crosslinks.

Appendices

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The following seven publications are included as appendices:
1. Tapered Rib Adiabatic Following Fiber Couplers in Etched GaAs Materials for Monolithic Spot-Size Transformers
2. High Speed Traveling Wave Electrooptic Intensity Modulator with a Doped PIN Semiconductor Junction
3. Traveling-Wave Electrooptic Intensity Modulator Using a Doped PIN Semiconductor Junction for DC to >40GHz Modulation Bandwidth
4. Reduced Coupling Loss Using a Tapered-Rib Adiabatic-Following Fiber Coupler
5. A Rib Optical Waveguide with Cutoff Mesa Isolation
6. An Integrated Optical XY Coupler for Phase-Sensitive Optical Power Combining and Suppression of Radiated Light
7. Attenuation Losses in Electron Cyclotron Resonance Plasma Etched AlGaAs Waveguides
8. Etching of GaAs/AlGaAs Rib Waveguide Structures Using $BCl_3/Cl_2/N_2/Ar$ Electron Cyclotron Resonance
9. Unlimited Bandwidth Distributed Optical Phase Modulators and Detectors: Design and Fabrication Issues

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